NASA-CR-202166

ANNUAL PROGRESS REPORT
TRANSPORT OF SOLAR IONS THROUGH THE EARTH'S MAGNETOSPHERE
GRANT NAGW-4177
(for period ending September 30, 1996)

1. PREFACE

This is a study of the injection into and subsequent transport through Earth's magnetosphere of solar wind plasma, as represented by protons (H^+) and alpha particles (He^{++}) with energies between 10 eV/e and 18 keV/e, using a particular set of archived data from the Lockheed Plasma Composition Experiment on the International Sun-Earth Explorer One spacecraft (ISEE 1) [*Shelley et al.*, 1978]. The data set presently covers slightly more than the first half of the almost 4 1/2 years of operation of this experiment (53 months) and will soon be extended to include the remainder as well. The format of these data is described in some detail in the appendix section of a recent publication [*Lennartsson*, 1994], and in full detail in a document accessible on the Internet, on WWW page ftp://sierra.space.lockheed.com/DATA/isee/Welcome.html.

This report covers efforts that are still under the first-year funding, since this initially three-year grant is presently in a one-year no-cost extension. The reason for this no-cost extension, which was requested by us, is that after we had already begun work under this science grant, we received another one-year NASA grant to archive our remaining ISEE data as part of a new Data Restoration Program by the Space Physics Division. Because that latter grant was a one-year effort only, and, more importantly, because it would significantly enhance the data base for our science study, we decided to let the archiving take precedence. Our work with the archiving is now near completion and we will soon be able to utilize the new data in the present study.

2. SCIENCE BACKGROUND

This study is an attempt to clarify and quantify the results of an earlier investigation by us of the fundamental topic of solar wind penetration of Earth's magnetopause [*Lennartsson*, 1992], one that was based in part on our first and rather primitive set of archival data from the early 80's and in part on specific event data on ion flows in Earth's magnetic tail. Our experiences from that work were the principal reason why we decided to produce a new and more advanced set of archival data for the NSSDC and for our own use. The first part of these differently formatted data was produced in 1991, using approximately the first half of our raw flight telemetry data, and the second and last part is being produced now.

Because of the ability of our ISEE instrument to differentiate between ions of solar origin, typified by He^{++} ions, and ions of terrestrial origin, typified by O^+ ions, and, equally importantly, because of the unique orbit of ISEE 1 (and ISEE 2), we were able to determine that the conditions under which solar plasma penetrates Earth's magnetopause are probably very different from what has been traditionally assumed. In a first tentative synthesis of our data *Lennartsson* [1992] argued the following points:

1. In terms of "open" and "closed", the magnetopause, specifically its tailward extension, is "open" to charged particle penetration at all times, regardless of the polarity of the IMF B_z (interplanetary magnetic field z-component in geocentric solar magnetospheric coordinates, or GSM coordinates, for short). In fact, according to our ISEE data, the tail plasma sheet contains the greatest number of H^+ and He^{++} ions, and the most solar-wind-like such ions (thermal energies comparable to solar wind bulk flow energies), during extended periods of positive, or northward, B_z, that is during periods when, traditionally, the magnetopause is thought to be "closed", because no "merging" is taking place between the IMF and Earth's magnetic field.

2. As the B_z turns negative, or southward, our data do not show increasing concentration of solar plasma in the tail plasma sheet, as would reasonably be expected within the framework of "dayside merging and nightside reconnection", but instead a decreasing concentration, manifested by an overall decrease in the plasma density, that is in the density of the dominant ion species H^+, as well as in the density of He^{++} ions. This process may well involve an actual decrease, not increase, in the rate of entry of solar plasma during southward B_z, the evidence is not yet clear on that point, but it seems to involve an increasing outflux as well. Part of the vanishing ions no doubt enter the inner magnetosphere at these times, populating the ring current, but some other part may exit the magnetosphere through the dayside magnetopause. The H^+ and He^{++} ions that remain behind in the plasma sheet have had their energy ("temperature") increased in the process.

3. It has long been known that the plasma sheet "thins" initially, after B_z turns southward [*Hones et al.*, 1971], usually associated with substorm "growth phase" [*McPherron et al.*, 1973], but the subsequently observed "recovery" some 10 to 30 minutes later [*Hones et al.*, 1971], associated with magnetic field dipolarization and substorm main phase onset [*McPherron et al.*, 1973], has been assumed to more than offset that initial particle loss. Our data show that this so called "recovery" is not sufficient; it probably only reflects a redistribution of the plasma within the reconfigured magnetic field (see below). According to our data, it usually takes many hours for the plasma sheet to regain its pre-storm density (and pre-storm energies), and a complete refilling only follows a northward turning of the B_z.

4. Most likely, the solar plasma does not enter the plasma sheet far downtail by first convecting through the tail lobes (while also flowing downtail along the magnetic field lines), as traditionally thought, but instead along the entire length of the tail flanks, through "slots" between the lobes and the plasma sheet proper, starting at the dayside cusp. This mode of entry, we believe, is not driven by the solar wind electric field (= negative cross product between flow velocity and IMF vectors), which might seem feasible only when B_z is southward, but by the electric field that is locally generated in the low latitude boundary layer (LLBL) on the tail flanks, by some kind of solar wind "frictional force", which probably works with both northward and southward B_z, perhaps even better with a northward field. This scenario is illustrated schematically in Figure 1 (figures are attached).

3. INITIAL NEW RESULTS

It is our belief that by using massive quantities of statistical plasma composition data, such as our archived ISEE data, and only that way, it will be possible to prove these points qualitatively and also to obtain quantitative measures of time scales and flow patterns. For example, the cross-tail portions of the particle convection in Figure 1 are qualitatively consistent with previously observed drift directions of tailward-flowing and strongly collimated beams of low-energy ions, observed by a particle instrument on ISEE 2 and inferred from our ISEE 1 data to be O^+ ions from Earth [*Orsini et al.*, 1990], but we expect to be able, eventually, to confirm this convection with data on the near-isotropic keV-type H^+ ions, most of which may be thermalized solar ions, by separating the rather slow drift from the spurious effects of ion gyration within density gradients. We have not reached that far yet, but we have uncovered other features of ion motion, related to motion along the tail and largely along the magnetic field, which are consistent with Figure 1 but seemingly inconsistent with a more traditional view of solar plasma entry.

One of the essential components of "magnetic merging/reconnection" is to have solar wind plasma convect through the tail lobes, from north and south, and converge in the tail midplane, at some distant but not precisely known location, probably a variable one, where a "neutral line" forms in the magnetic field, stretching across the tail from dawn to dusk, possibly along some curved shape. From this location, solar wind particles are expected to jet earthward along the magnetic field, while at the same time being convected into the central plasma sheet by a large-scale dawn-dusk electric field imposed from the solar wind (usually under the assumption that the IMF B_z is southward; see for example *Cowley* [1980],). As these particles are being convected into the plasma sheet, they are assumed to undergo energy and angle scattering and become the main component of the virtually isotropic population of central plasma sheet particles.

This scenario thus implies, or at least strongly suggests, that the earthward fluxes of ions must be the most strongly collimated and intense at the outermost northern and southern edges of the plasma sheet, in what is now usually referred to as the "plasma sheet boundary layer" (PSBL in Figure 1a), in order for these to be the source of the isotropic fluxes in the center. That is, the ions near the outer edges must have a sufficiently high phase space density within a norrow earthward velocity cone to be able to fill the entire unit sphere with the kind of differential flux or phase space density that is observed in the central plasma sheet. Since collimated field-aligned fluxes are made up of ions with small gyrational energy, this also means that higher fluxes should be found at lower ion beta, that is at a lower ratio of ion gyrational energy density (perpendicular ion pressure) to magnetic field energy density (magnetic pressure). Observations by many particle detectors, including several on the ISEE 1 and 2, have indeed found the most strongly collimated ion fluxes near the edges of the plasma sheet, pointing earthward, but whether the intensity is sufficient to account for isotropic central plasma sheet fluxes has remained an open question. Our data now show that it is not sufficient.

Figure 2 shows scatter plots of H^+ bulk velocities along the GSM (geocentric solar magnetospheric) x-axis, which points earthward (along the earth-sun line) for negative (nightside) x-coordinates, sorted according to the measured ion beta value (magnetic field data from the ISEE 1 Fluxgate Magnetometer [*Russell*, 1978]). The beta value here includes not only the H^+ ions, which usually contribute the largest partial pressure, but also He^{++}, He^+, and O^+ ions. This illustrates our finding that H^+ ions are most often isotropic, or nearly isotropic, everywhere in the plasma sheet (inside of the ISEE 1 apogee at 23 R_E), but when large bulk flows do occur, these are typically earthward and occur most often at low beta (<0.1) and during times of elevated geomagnetic activity (and southward B_z), as measured by the hourly AE index here. These earthward bulk flows are consistent with reported occurrences of earthward "jetting" of ions along the tail magnetic field.

Figure 3 shows the typical (average) peak differential flux of H^+ ions in the earthward (top) and tailward (bottom) directions, again sorted by measured ion beta, but also by the direction of the concurrent hourly average IMF B_z, rather than by geomagnetic activity. The IMF is from the NSSDC OMNI file [*Couzens and King,* 1986]. The "peak flux" here refers to the maximum flux, either earthward or tailward, of all samplings during a complete energy-spin-angle cycle for H^+ ions, a cycle that may be repeated some 3 to 15 times per hour (each ion sampled separately), depending on instrument mode of operation. The peak flux may occur in any energy channel, within the total range from 10 eV/e to 18 keV/e, but occurs most typically around a few keV for earthward moving H^+ ions.

It is clear from Figure 3 that earthward fluxes of H^+ ions, the dominant ion species in the solar wind, and almost always the dominant one in Earth's tail plasma sheet as well, are typically not stronger but weaker at low beta, near the outer edges of the plasma sheet, than they are in the central plasma sheet, at beta >0.1. This is not what one would expect if the former were the source of the latter.

By contrast, O^+ ions from Earth, streaming tailward, do have maximum flux intensities at low beta, as shown in Figure 4. The number density of O^+ ions is higher at high beta, in the central plasma sheet [*Lennartsson,* 1994], and the mean energy ("temperature") is also higher there than it is at low beta [*Lennartsson,* 1994], but the peak flux at low beta, although concentrated to a narrow beam, has at least sufficient intensity to be a significant source for O^+ ions in the central plasma sheet. This is more than can be said for the earthward flux of H^+ ions at low beta.

4. WORK IN PROGRESS

We believe that we will be able to show convincingly, especially after we have completed the second round of data archiving, that earthward "jetting" ions, so often observed near the outer edges of the plasma sheet during plasma sheet "recovery", are not newly arrived solar wind particles about to enter the plasma sheet, as commonly thought, but instead old plasma sheet partricles streaming away from the tail midplane following the dipolarization of the tail magnetic field. We also hope to be able to show why this is an intrinsic part of the substorm mechanism.

Figure 5 illustrates schematically what we believe happens with the plasma sheet particles when the near-earth tail magnetic field dipolarizes: After having been diamagnetically confined by the tail-like magnetic field in the lobes during the process of plasma sheet thinning (panel a), which involves a reduction in both the overall particle density and the spatial thickness [*Hones et al.*, 1971], the remaining particles are able to escape earthward and poleward when the local magnetic field becomes more dipole-like (panel b), thereby further reducing the plasma density and, we believe, the ratio between the perpendicular plasma pressure and the magnetic field pressure, that is, reducing the local beta value, leading to a (temporary) collapse of the previous pressure balance. A spacecraft situated in one of the tail lobes at this time, close to the plasma sheet (panel a), will thus experience an apparent plasma sheet "recovery" (panel b), where particles with larger field-aligned and earthward velocity tend to appear before those with smaller such velocity. That is, the seemingly "outermost" particles will tend to have the smallest pitch angle, simply because of the time-of-flight effect.

This scenario may seem to involve conventional reconnection of "open" tail magnetic field lines, but we do not anticipate that the magnetic field and the plasma actually "move together", as in the conventional interpretation of "reconnection", but rather that Earth's magnetic field reclaims territory previously held by the vanishing portion of the diamagnetic plasma sheet. That same territory will be yielded to plasma again later, as new solar wind particles arrive from the flanks (Figure 1), but that process may take many hours and may require that IMF B_z turns northward again. As far as we can envision our different interpretation of "reconnection", there is no need to have a near-earth "neutral line" form either.

This diamagnetic collapse of the near-earth plasma sheet is in our view a consequence of plasma sheet thinning, following a southward turning of the IMF B_z, and the mechanism of substorm "expansion". The mechanism of plasma sheet thinning itself, that is substorm "growth", is more difficult to illustrate in a two-dimensional cartoon, and we do not yet have a clear picture of what really happens, but we are investigating a scenario that can be outlined on the basis of Figure 6.

The tail cross section drawn in Figure 6 is based on three hypothetical and not necessarily realistic assumptions: 1. The northern and southern edges of the plasma sheet, bordering the lobes, are on closed geomagnetic field lines that connect either to the magnetopause on the tail flanks or, in the case of field lines closer to the midnight plane (GSM x-z plane), to some distant point inside the tail (at large negative x). 2. Geomagnetic field lines are good electric conductors. 3. These border field lines are all at either of two constant electric potentials (dashed lines), a high potential at $y < 0$ (dawnside) and a low potential at $y > 0$ (duskside), implying that the solar wind plasma on either flank (actually the solar wind plasma in the magnetosheath) is also at constant potential along the respective flank.

The third of these assumptions is the most far-fetched one, since the solar wind electric field is typically inhomogeneous (as are the IMF and the solar wind density), and this inhomogeneity is carried along the magnetotail flanks by the solar wind bulk motion. However, the significant point that Figure 6 may help to illustrate is the following: The closer the tail cross section is to Earth, the larger is that fraction of the border magnetic field lines which connect to the magnetopause on the tail flanks and, moreover, the further upstream do some of these field lines connect to the solar wind potential. This, we believe, has the important consequence that when an increased dawn-dusk electric field is carried down-tail by the solar wind, after a southward turning of IMF B_z, the near-earth part of the magnetotail is the first to experience the effects, including increased earthward and sunward convection near the center of the plasma sheet (near the GSM x-axis), due to the increased potential difference between magnetic field lines connecting to the dusk and dawn flanks, respectively. If one is willing to accept that earthward/sunward convection is temporarily larger in the near-earth plasma sheet than it is further down-tail, then it seems only natural that the near-earth plasma sheet must undergo local thinning in terms of conservation of particles. At least that is our current line of reasoning.

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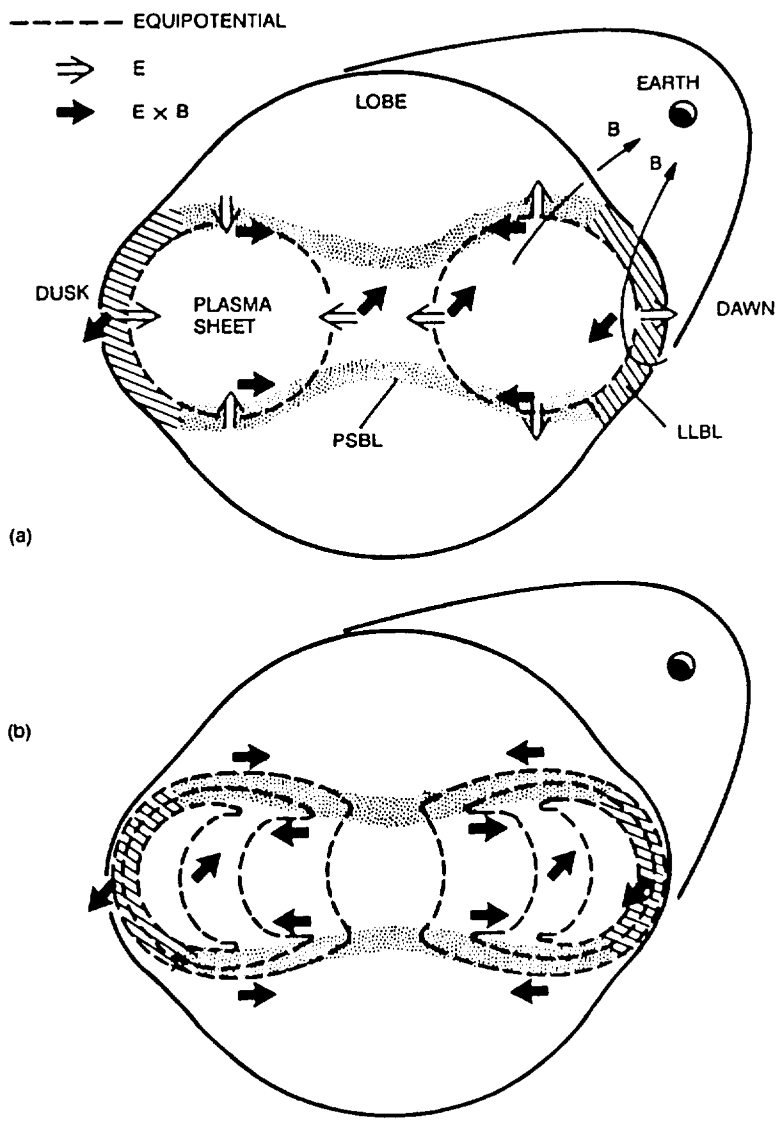

Figure 1. Cross sections of a geomagnetic tail with internal closure of equipotentials (tubular) associated with electric field in the low latitude magnetopause boundary layer (LLBL).
(a) Conceptual geometry showing electric field direction (open arrows) and E×**B** drift (solid arrows).
(b) Equipotentials adjusted to fit observed cross-B drifts in central plasma sheet [*Lennartsson*, 1992].

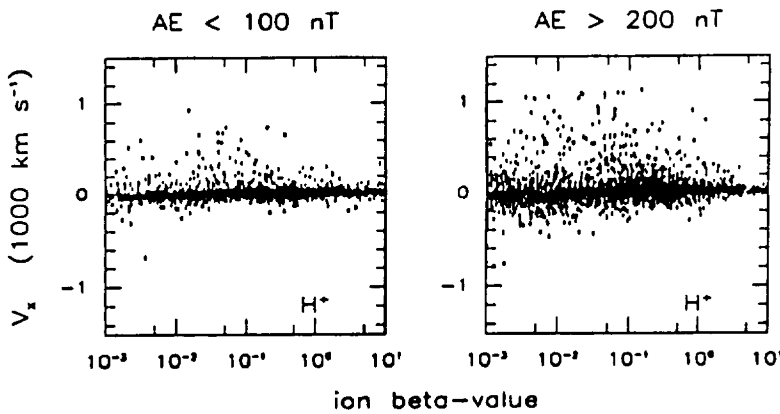

Figure 2. Drift velocity of 0.1- to 16-keV H^+ ions along GSM (and GSE) x-axis in central tail, inside of 23 R_E, sorted by measured ion beta (adding partial pressures of the four principal ions; see text) and by concurrent hourly AE (auroral electrojet) index.

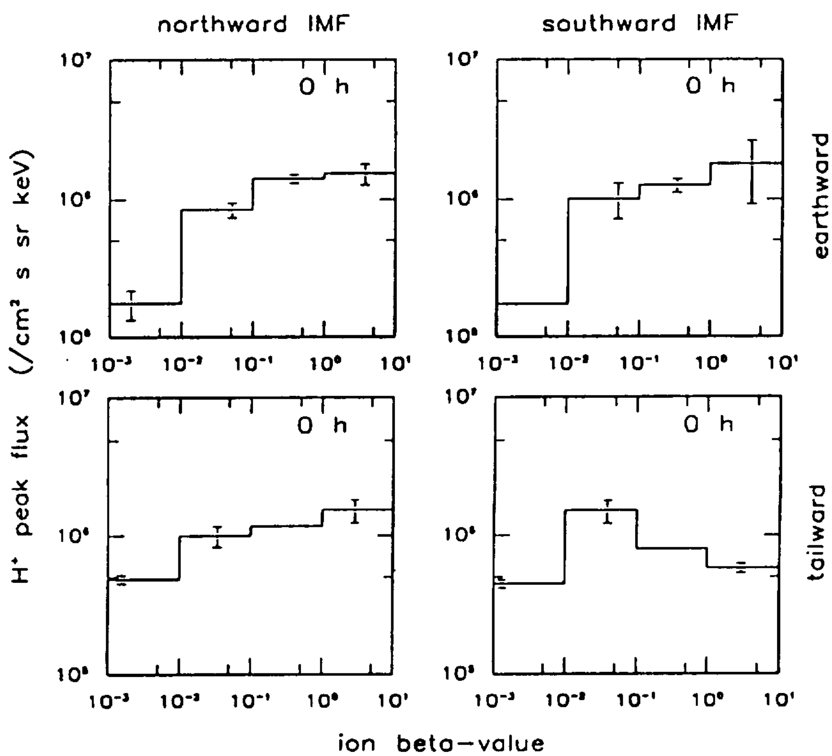

Figure 3. Averages of corresponding peak differential H^+ flux (peak flux per velocity moment integration) in the (top) earthward and (bottom) tailward directions, sorted by same beta values but by direction of concurrent hourly average IMF ("0 h" indicates no time shift) rather than by AE. Error bars indicate standard deviation of mean ($\pm 1\sigma$). Samplings include all energies between 10 eV and 18 keV here, but are limited to those moment integrations that covered all pitch angles.

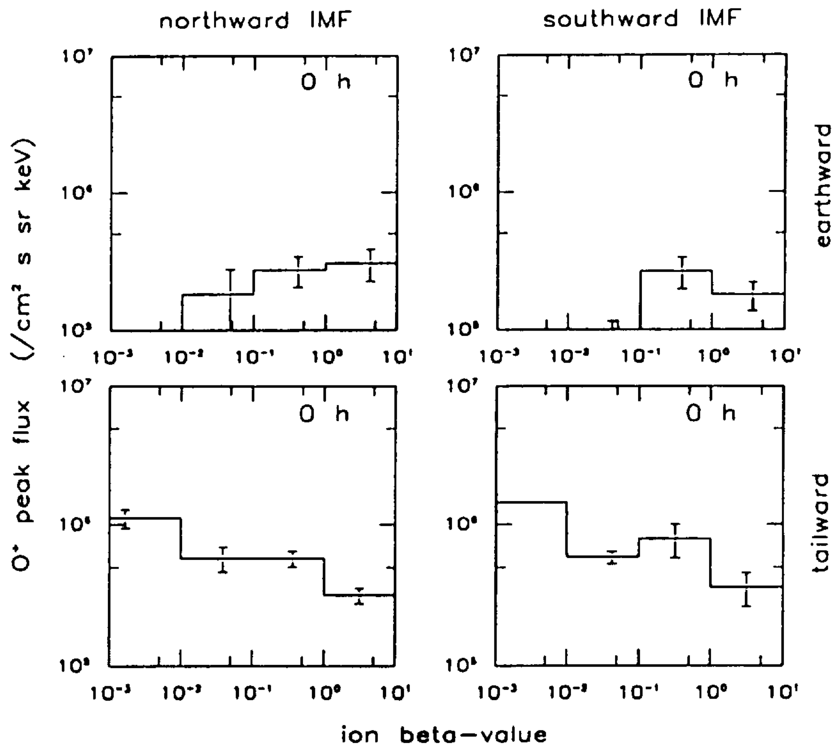

Figure 4. Same as Figure 3 but for O^+ ions. Differential flux of O^+ ions is usually greater in the tailward than earthward direction and often greatest at low energy (few hundred eV), especially at low beta.

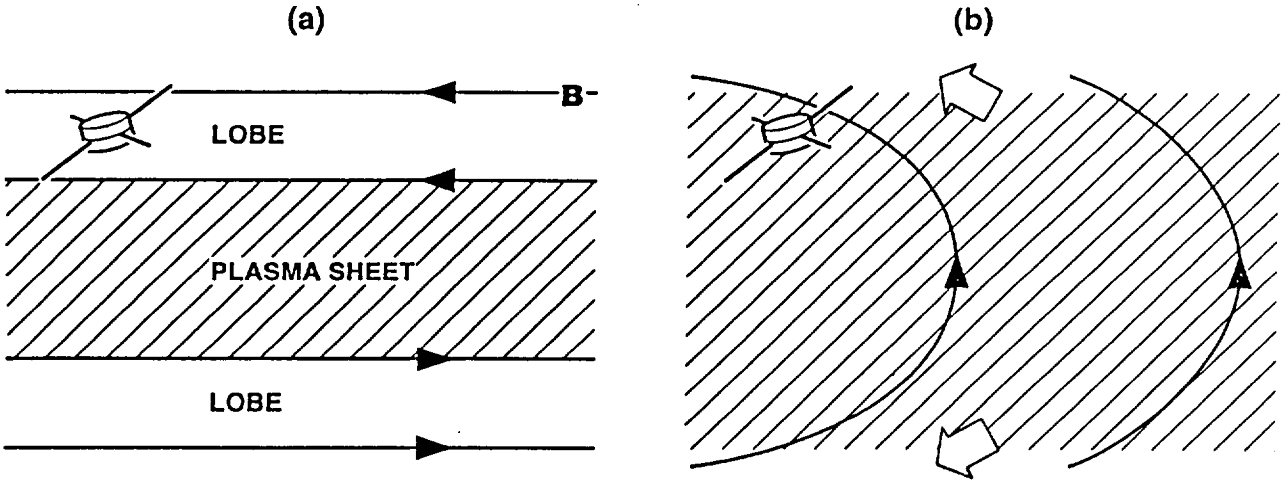

Figure 5. (a) Plasma sheet (cross hatched area) in a sate of thinning due to increased earthward and sunward convection (to the left), leaving observing spacecraft in tail lobe. Direction of tail lobe magnetic field (**B**) indicated by thin lines with solid arrow heads. (b) Plasma sheet engulfing spacecraft again by expanding (open arrows) along magnetic field lines that are becoming increasingly dipole-like.

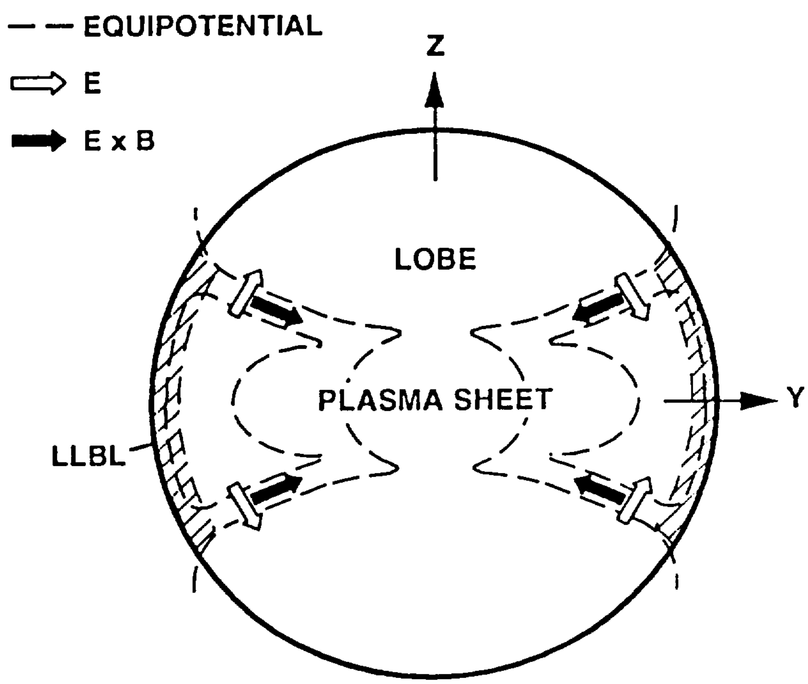

Figure 6. Similar to Figure 1, but viewing downtail, away from Earth (along negative GSM x-axis), and showing outermost equipotentials (open dashed contours) connected to solar wind, assuming dawn-dusk directed (from left to right) electric field within solar wind itself, that is, assuming southward IMF B_z along tail flanks (where the IMF may be "merged" with the geomagnetic field). These equipotentials only apply to hypothetical homogeneous fields in solar wind [*Lennartsson*, 1994]. Conditions become more complex when solar wind fields are inhomogeneous, due to the motion of the solar wind along the tail flanks (see text).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 30, 1996

3. REPORT TYPE AND DATES COVERED
Annual Progress

4. TITLE AND SUBTITLE
TRANSPORT OF SOLAR IONS THROUGH THE EARTH'S MAGNETOSPHERE

5. FUNDING NUMBERS
G: NAGW-4177

6. AUTHOR(S)
O.W. Lennartsson, Principal Investigator

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA Headquarters

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited/Unclassified

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Report reflects the status of the grant as of the report date.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102